THE USE OF RESPONSE SURFACE METHODOLOGY (RSM) TO OPTIMIZE THE TWIST DRILL GEOMETRY IN SINGLE SHOT DRILLING OF STACKED ALUMINA-CARBON COMPOSITE LAYER

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DECLARATION

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TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

ABSTRAK

Penggerudian secara berlapis merupakan amalan yang diguna secara meluas dalam industri aeroangkasa. Malah, keserasian gerudi untuk menggerudi kedua-dua bahan yang diperbuat daripada komposit dan logam masih muncul sebagai halangan yang besar kepada industri tersebut. Dalam kajian ini, berdasarkan kuasa tujahan yang dihasilkan semasa meggerudi CFRP/Al, kesan pengubahan geometri dan parameter gerudi *twist* dikaji secara mendalam. Kajian ini bertujuan untuk menentukan nilai-nilai optimum bagi parameter-parameter ujian tersebut melalui penggunaan kaedah statistik (RSM) oleh reka bentuk komposit pusat (CCD) yang digunakan untuk memilih dua puluh uji kaji untuk menilai kepentingan geometri alat pada tujah berkuat kuasa semasa operasi penggerudian.

Hasil analysis ANOVA menunjukkan kuasa tujahan maksima dan kekasaran permukaan merupakan faktor yang paling mempengaruhi nilai-nilai optimum bagi parameter-parameter yang telah diuji untuk Aluminum dan CFRP. Berdasarkan analysis kuasa tujahan dan kekasaran permukaan, parameter alat yang paling optimum ialah 6° pelepasan utama, 130° sudut titik, 30° sudut tepi pahat. Parameter untuk kelajuan dan kadar suapan adalah tetap iaitu 2600 rpm kelajuan and 130 mm/min kadar suapan.

ABSTRACT

Stacked up drilling is being practiced widely in the aerospace industry, but the compatibility of the drill to compensate the widely differing properties of composite and metal is still a major challenge to the industry. In this study, the effect of the twist drill geometry and drilling parameters are being investigated based on the generation of thrust force signature during drilling of CFRP/Al. The study was aimed to establish the optimum values of those testing parameters through the use of statistical method of response surface methodology (RSM) by central composite design (CCD) is used to select twenty runs of experiment to evaluate the significance of tool geometry on thrust force during the drilling operation. The CCD is a very effective design for use a second-order response surface model.

Based on ANOVA, it is found that the maximum thrust force and surface roughness is the most influencing factor of optimum value for tested parameters for Aluminum and CFRP. Through the analysis of thrust force and surface roughness, it is concluded that the optimum tool parameters selection includes primary clearance of 6°, point angle of 130°, and chisel edge angle of 45°. The parameters for speed and feed rate are fixed at 2600 rpm speed and 130 mm / min feed rate.

Chapter 1 INTRODUCTION

1.1 Stacked up Material in Aerospace Industry in General

Aerospace is the human effort in science, engineering and business to fly in the atmosphere of Earth (aeronautics) and surrounding space (astronautics). Aerospace organizations research, design, manufacture, operate, or maintain aircraft and/or spacecraft. Aerospace activity is very diverse, with a multitude of commercial, industrial and military applications. The aircraft industry is the industry supporting aviation by building aircraft and manufacturing aircraft parts for their maintenance. This includes aircraft and parts used for civil aviation and military aviation.

An aerospace manufacturer is a company or individual involved in the various aspects of designing, building, testing, selling, and maintaining aircraft, aircraft parts, missiles, rockets, or spacecraft. Two materials play major roles in modern aerospace is aluminum alloys for airframes and skin, and composites for structures. For aluminum alloy, the most common alloy used in aerospace is 7075. It possesses strong and high strength compare to many steels, has good fatigue strength, average machinability and has less corrosion resistance as compare to other aluminum alloys, making it possible to strengthen the aircraft structures **[1]**. Aluminum is still lightweight, technically advanced in terms of forming and alloying, and it relatively low cost, especially when compared to titanium and composites.

Carbon fibers are the reinforcement of choice for aerospace composites because of the drive to increase fuel efficiency and to improve the aerodynamic performance of aircraft **[2].** Carbon fibers in aerospace composites can be long and continuous, or short and fragmented, and they can be directionally or randomly oriented. In general, short fibers cost the least and fabrication costs are lowest. But due to low material and fabrication cost, short fibres are preferred generally. With proper selection and placement of fibres, the prominent advantage is that the composite can be stronger and stiffer than steel parts with similar thickness.

The response surface methodology (RSM) explores the relationships between several explanatory variables and one or more response variables. The main idea of RSM is to use a sequence of designed experiments to obtain an optimal response. The RSM includes the regression analysis and the statistical design of experiments for constructing the global optimization of the testing parameters **[3].** It is also one of the most widely used methods to solve the optimization problem in the manufacturing environments **[4,5].** Statistical approaches such as RSM can be employed to maximize the production of a special substance by optimization of operational factors. In contrast to conventional methods, the interaction among process variables can be determined by statistical techniques

Drilling is one of the most fundamental machining technologies and is moving toward high precision/high speed applications for productivity enhancement. Drilling is also a cutting process that uses a drill bit to cut a hole of circular cross-section in solid materials. The drill bit is usually a rotary cutting tool, often multipoint. The most common type of drill type used in aircraft drilling is twist drill. Drilling of composite material and aluminum stack is a challenge to manufacturing engineers. Drilling of CFRP is manageable but the minute drill hits the Al or Ti, those hot and continuous chips destroy the hole. The parametric influences on thrust force, torque as well as surface finish were experimentally evaluated. The experimental results show that the quality of holes can be improved by proper selection of cutting parameters.

1.2 Research Background

In the aircraft industry, where mechanical fastening of joined components is a necessity and the drilling of many thousands of holes per aircraft is, there are many factors that should be considered. One shot drilling technique is widely applied on the metal and composite materials, such as aluminum and carbon fiber-reinforced polymer (CFRP). Both materials are drilled in a single shot and stacked up **[6].** The drilling method, tools and parameter selected are essentially important to ensure that the tight tolerance of an aircraft is being fulfilled. The response surface methodology (RSM) is introduced as an efficient method for investigating and optimizing important parameters to optimize the twist drill geometry.

One shot drilling technique is the best process to be chosen and ensures a more proper hole alignment and thus capable of producing holes with higher quality and accuracy if all the joined parts are either all-metal or all-composite. However, the aircraft industry still has problems to producing optimum and consistent hole quality. Besides having a relatively small and tight holes' tolerance, the challenge imposed on the stacked-up materials is due to their vast difference in properties. Now, carbon fibers are the reinforcement of choice for aerospace composites because of its high strength-to-weight and stiffness-to-weight ratios. Carbon fibers in aerospace composites can be long and continuous, or short and fragmented, and they can be directionally or randomly oriented. However, at certain deflection limit, carbon fiber will shatter while aluminum will bend. Besides, carbon composites are relatively brittle. They have no yield behavior and resistance to impact is low than aluminum, Aluminum has a much better resistance of heat than carbon fiber **[7].**

Moreover, the aircraft industry is still exploringe to identify the best drilling parameter and drill geometry for the optimum holes' quality result. The problem is that the industry common practice to scrap the materials when the holes do not conform to specification. There is also not much of research work being carried out on drilling of aluminum / CFRP stack-up. Thus, the research should find out about the influence of various combinations of process parameters on hole quality and drill geometry.

1.3 Problem Statement

Nowadays, the type of drilling that aircraft industry uses is single-shot drilling of stack-up materials. The problem of the aircraft industry such as the rapid tool failure and poor hole quality when the single-shot drilling is carried out on two different materials with very contrast properties. Furthermore, the drilling process is carried out by trial and error method or dependent on the experience of the operators. The high cost of production occurs when the hole quality and tolerance are inconsistent. Meanwhile, the performance of single-shot drilling is mainly contributed by the variation in setting the drilling geometry and parameters, continuous research on the optimum drilling parameters and drill geometry will not only provide a guide to the operators on how to conduct a proper drilling operation but also will leave a significant impact to the industry.

1.4 Objectives

1. To identify the optimum drill geometry parameters of twist drill to conduct the single shot drilling on stack-up materials.
2. To determine the effect of the drill geometry parameters on the thrust force produced
3. To identify the relationship of thrust force to hole quality of single shot drilling process.

1.5 Scope of Work

In my research, the main objective is to utilize the force generated during drilling as a form of indicator of the occurrence of tool wear besides monitoring the quality of the hole. Thus, the study area will find the optimum drill geometry in a single shot drilling of stack CFRP and aluminum material. The properties of aluminum and carbon fiber will be studied individually to explore the optimum operating range for both materials. There are two methods will be used to evaluate the holes' quality, which is by observing the force signature generated from dynamometer during the drilling process and offline measurement on possessions like surface roughness.

Chapter 2 LITERATURE REVIEW

2.1 Drilling on CFRP

Carbon Fiber Reinforced Plastic (CFRP) composite materials have potential applications in aircraft industry. Meanwhile, carbon fiber reinforced polymer (CFRP) composite material have excellent strength to weight ratio, damage tolerance, fatigue and corrosion resistance. In order to minimize these machining problems, there is need to develop scientific methods to select cutting conditions for damage-free drilling of composite materials, the tool selection and parameters will largely correspond to the machining process quality. In the research conducted by **Biren Desai, Jaypalsinh Rana and Hiren Gajera [8],** the most effective parameter during measuring circularity and feed is most effective parameter hole size through drilling operation. They discuss about an application of the full factorial design for optimizing the cutting parameters in drilling operations performance measures circularity and hole size. . In the research conducted by, **Vaibhav A. Phadnis, Farrukh Makhdum, Anish Roy, Vadim V. Silberschmidt [9],** thrust force, torque and delamination damage increase significantly with feed rate, but decrease slowly with increasing cutting speeds. Thus, for a good drilling of CFRP, low feed rate (< 150mm/min) and high cutting speed (>600rpm) should be selected for an ideal result of CFRP drilling. **Marta Fernandesa, Chris Cook [10]** have applied the study of drilling of CFRP on varying thickness. They research about the chip formation during drilling operation to high tool wear rates was interrelated. Tool wear is very related to delamination because the force required to cut the material increases with tool wear. In their research, the thinner workpiece will result in higher thrust force due to wear.

2.2 Drilling on Aluminum

Aluminum is used in many engineering areas to create different products and it is important for the ecosphere economy. For aluminum alloy, the most common alloy used in aerospace is 7075. Aluminum 7075 is commonly used in aircraft assembly due to its strong and high strength advantage compare to many steels, possesses good fatigue strength and average machinability. Research has been done to study the response surface methodologies for minimizing the burr height and the surface roughness in drilling Al-7075. In the research conducted by **Ugur Koklu [11],** it proposed that the optimization results showed that the combination of low cutting speed, low feed rate and high point angle is necessary to minimize both burr height and surface roughness. Besides, research also has been done to study the effect of feed rate and drill diameter on burr height and surface roughness of drilling holes. In the research conducted by **Ugur Koklu [11],** it proposed that the drilling process produces burrs on both the entrance and exit surface of the workpiece, but most problem associated to burr are caused by the exit burr as the burr is larger at the exit than the entrance. Severe burr formation will lead to deterioration of the surface quality, dimensional distortion on the part edge, assembly and handling error. Moreover, **Redouane Zitoune, Vijayan Krishnaraj, Francis Collombetthe [12]** supposed in their paper that most common drilling condition ascends in aluminum is the built-up-edge and burr at the exit side of the hole. Though, BUE can be reduced by increasing spindle speed and the exit burr can be reduced if the feed rate is increased. Next, **K. Anand Babu, Dr. G. Vijaya Kumar [13]** have applied a different approach which is Taguchi Fuzzy approach to study the optimum cutting parameters. The controllable parameters are speed, feed rate, tool material, point angle and cutting environment. As a result, the best required cutting parameters is 500rpm, 0.2mm/rev feed rate, TiAlN-HSS tool material, 118°-point angle and under diesel cutting environment.

2.3 One Shot Drilling of Stacked up Material (CFRP/AL)

Drilling of CFRP and aluminum is a challenge to manufacturing engineers. Drilling CFRP/AL stacks, so, has usually involved multistep operations to permit the use of drill tools optimized for both material. The selection of process parameters is important due to the difference of material properties. In the research, the study of critical thrust force is used as a target to measure the drilling quality stacked up materials. In the research paper by **Benezech et al [14]** paper explains that the holes for stacks are manufactured via a multi-shot routine and this requires pre-drilling of each material followed by a de-burring cycle. The stack is then assembled and temporarily held together before hole reaming. Even though, it is difficult to achieve a high tolerance level due to different elastic moduli and coefficient of thermal expansion of materials in the stack. Manual drilling at low cutting speeds with low feed rates are usually used which results in an increase of production time. Hence, single-shot drilling is done to minimize the positional errors and production time, and to obtain close tolerances. Allowing to the result, the thrust force and torque is double at low feed rate (0.05mm/rev) but tripled at higher feed rate (0.1mm/rev and 0.15mm/rev). This is because of the higher effect of the fiber and reduced effective clearance angles of the drill, thereby creating frictions between the CFRP/Al stack. In the research conducted by **Ginger Gardiner [6],** in order to dry-drill H8 holes in composite-metal stacks in a single operation, the problems traditionally solved by using different tools, multiple drilling steps and lubricant had to be addressed in tool design and in control of drilling process parameters, specifically, rotational speed and feed rate. This required a fundamental understanding of the drilling processes for metals and composites.

2.4 Drill Bits

2.4.1 Twist Drill Geometric Design

The kinematics of drilling is a process of using a rotating drill bit to create or enlarge existing round holes in a workpiece **[16]** and drill bits are cutting tools used to create cylindrical holes, mostly for circular cross-section **[17]**. With the aid of one or more cutting lips and flutes, the spiral (or rate of twist) in the drill bit serve as a function of controlling the rate of chip removal and access of a cutting fluid **[16]**. The type of drill commonly used in the industry is twist drill [**17**]. The varying parameters which will contribute to the twist drill geometric design includes helix angle, primary clearance, point angle and chisel edge angle.

2.4.2 Drill Bits Material Selection

The life of a drill is dependent on its hardness, toughness, wear and thermal resistance [**16**]. When opting for a suitable drilling tool material, it is essential for the hardness value of the tool to be higher than the material of the workpiece so that the tool can drill and remove the unwanted area of the workpiece without causing wear and torn to the drilling tool. The table 2.1 below shows the hardness value of different types of drilling tools and stacked up material.

Table 2.1: Hardness of Drill Bits and Stacked-up Material

Type of Material		***Hardness (HRC) 150kgf***	***Hardness (HRB) 100kgf***	***Vickers Hardness (HV) (converted from HRC or HRB)***
Drilling tool	*High Speed Steel (HSS)*	*63-65*	*-*	*775-834*
	Tungsten Carbide	*89-108*	*-*	*2371- 5612*
	Polycrystalline Diamond (PCD)	*673*	*-*	*22821641*
Stacked-up	*Carbon Fiber Reinforced Plastic*	*-9*	*75*	*136*
	Aluminum 2 series (Al 2024)	*-9*	*75*	*136*
	Aluminum 7 series (Al 7075)	*5*	*87*	*171*

From figures 2.1 and 2.2, PCD which is the hardest tooling material among HSS and cemented carbides, possess the least toughest property as it undergoes a sharp deformation at temperature of 600°C. On the other hand, HSS and cemented carbides are capable of performing better at high cutting speed **[16]**. **Christopher Tate [18]** states that the selection of tool material is also dependent on the number of hole to be drilled and number of hole size. High performance carbide drill has the advantages of having the highest penetration rate and shortest cycle time, but it is costly. Therefore, if the number of holes to be drilled is low, it is appropriate to select alternative like HSS drill due to its cost-effective advantage. In terms of hole size, it is suggestable to select HSS drill if the hole size is between 12mm to 24mm as it is expensive to fabricate carbide drills above 12mm. In **Davim and Reis [19]** research, it proves that helical flute carbide drill is better because of the hot hardness when compare to HSS drill.

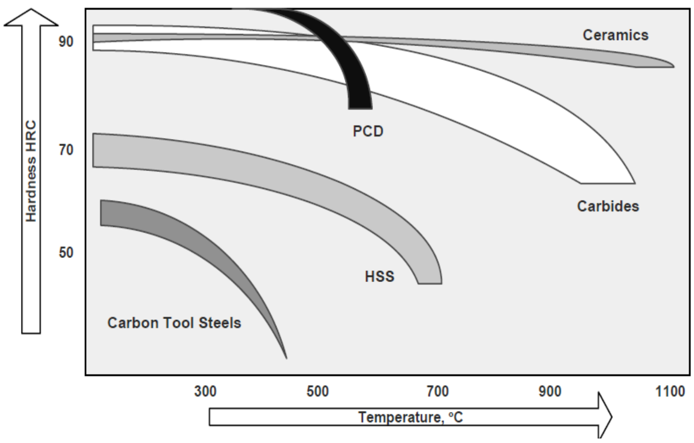

Figure 2.1: Relationship between Hardness of Drill Material and Temperature**[15]**

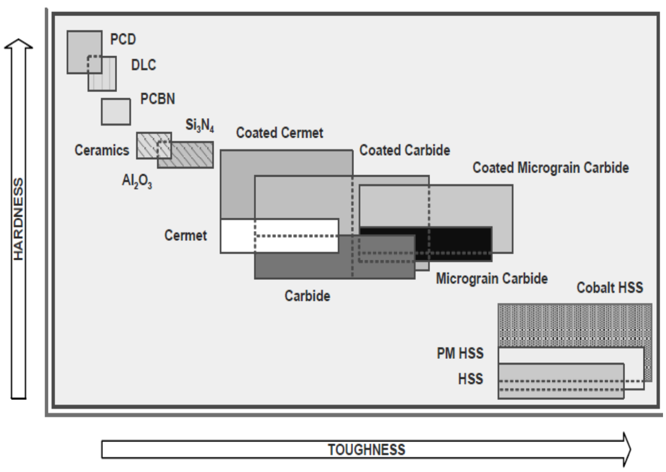

Figure 2.2: Relationship between Hardness and Toughness of Drill Material **[15]**

2.5 Effect of Drilling Parameters and Tool Geometry on Thrust Force, Surface Roughness and Chip Breakability on Stacked-up CFRP and Aluminum

Thrust force is the signature generated from dynamometer at real time to monitor the drilling operation of the stacked-up materials. Based on the tabulation of data in table 4, the thrust force recorded during drilling of aluminum was found to be two to three times higher than those recorded during drilling of the composite material. The thrust force generated while drilling CFRP is within the range of 40N to 300N, while a range of 180N to 658N are recorded for drilling of aluminum. Besides the mechanical properties of the stacked-up material, the thrust force is influenced by the parameters and tool geometry set.

In **M. Montoya & M. Calamaz & D. Gehin & F. Girot [20]** research, it is concluded that abrasion was the strongest wear mechanism observed in CFRP/AL drilling, which is due to highly abrasive properties of carbon fibre. The CFRP damage at the hole entry is directly related to the aluminum chip evacuation. **Redouane Zitounea et al [21]** found that the increase feed rate will lead to a significant increase in the value of the roughness, regardless of the type of drill used.

Chip breakability is another factor which influenced the quality of holes produced. **R. Zitounea, V. Krishnarajb, F. Collombeta, S. Le Roux [22]** mentioned that the feed rate and the drill diameter have an effect on chip breakability because of the increase in cross sectional area of chip whereas effect of spindle speed on chip breakability seems to be smaller. Generally, discontinuous chips or small well broken chips are more desirable for aluminum because when the chips are smaller in size, they can move through the flutes more easily, decreasing the torque requirement and temperature and eventually reducing the risk of drill breakage. Meanwhile **R. Zitoune, N. Cadorin et al [23]** found that the presence of continuous chips in aluminum at low feed rate impact the hole quality of the composite by the presence of the peel up delamination at the top of the hole. On top of that, **R.Zitoune et al** deduced that the efficiency of vacuum system is reduced with the presence of continuous chips as the dust quantity in the air increases**[22]**. Hence, in order to compensate both the aluminum and CFRP hole quality, the most optimum parameter is with the use of higher feed rate (0.1mm/rev). Both surface roughness and chip breakability are found to be highly dependent on feed rate but not spindle rate.

On the topic where the hole diameter of metal hole is consistently larger than the composite, recent article by **Ginger Gardiner [6]** explains that this is due to the fact that the fibres flex back into the hole after a few days. Furthermore, during the evacuation of aluminum chips, it affects the hole quality of CFRP directly, at both the hole entry and the wall of the hole.**[24] Lin Zhang et al** explained that the defects which are found in the CFRP holes is erosion, flash, tearing whereas Aluminum appear to have adhesive material and large burr on the hole surface.

Tool geometry design also influence significantly to the thrust force generated during drilling of stacked-up material. There are four tool geometry factors which are considered in tool geometry, which are the point angle, helix angle, chisel edge angle and primary clearance. Studies by **W Chen** suggested that an increase in point angle will led to an increase in thrust force and a reduction in torque, while an increase in helix angle and chisel edge result in a decrease in thrust force and torque **[30].** Lastly, primary clearance is important to keep the drill flank from rubbing against the workpiece. A large clearance angle will improve the tool life as friction is reduced but as the clearance angle increases, the strength of the tool decreases **[32].**

In this study, initial deduction made is that thrust force has a direct relationship with surface roughness and chip breakability. Hence by monitoring the thrust force, the hole quality of the stacked-up material can be predicted.

Table 2.2: Tabulation of Thrust Force for One Shot Drilling on Stacked-up CFRP and Aluminum **[12, 25-28, 33-35]**

No	Stacked-up Sequence	Tool Diameter (mm)	Thickness and Type of Material		Maximum Thrust Force (N)		Type of Tool Geometry	Parameters				
			CFRP (mm)	**Al (mm)**	**CFRP**	**Al**		**Feed rate (mm/rev)**	**Spindle speed (rpm)**	**Point angle**	**Helix angle (°)**	**Chisel edge angle(°)**
1	CFRP < Al	6.35	4.2 (uni)	3 (Al2024)	1. 80 2. 100 3. 122	1. 180 2. 330 3. 486	1. Twist drill double cone drill	1. 0.05 2. 0.10 3. 0.15	2020	90 132	-	-
2	CFRP < Al	6	4.35(uni)	3 (Al2024)	1. 108 2. 142 3. 180	1. 285 2. 486 3. 658	1.Coated drill 2.Uncoated drill	1. 0.05 2. 0.10 3. 0.15	2750	136	-	-
3	CFRP < Al	8	4.2 (uni)	3 (Al2024)	100	250	1.Plain carbide	0.1	1050	118	-	-
4	CFRP < Al	6	7 (woven)	14 (Al7010)	1. 40 2. 100 3. 60 4. 70	1. 120 2. 180 3. 140 4. 140	1. coated twist drill 2.diamond uncoated 3.TIALCrN uncoated 4.AlTiSiN-G uncoated	0.04	3000	124	30	-
5	CFRP < Al	6.35	4.2 (uni)	- (Al2024)	50	300	1.Twist drill (tungsten carbide)	0.05	2020	90 132	-	-
6	CFRP < Al	6.8	16.8	10 (Al2024)	300	450	1.Solid carbide standard drill	0.06	3500	-	-	-
7	CFRP < Al	6.8	16.8	10 (Al2024)	250	300	1.Solid carbide drill coated with TiCN	0.06	3050			
8	CFRP < Al	9.53	8.74 (uni)	6 (7075-T651 Al)	1. 100 2. 175	1. 200 2. 325	Diamond coated drill bit with double tip point angles	1. 0.02 2. 0.08	2000	1st - 130 2nd - 60	30	-

Chapter 3 METHODOLOGY

3.1 Overview of Methodology

This chapter presents the overall approaches used in this research to study the effect of twist drill geometry and drilling parameters on thrust force in single-shot drilling of stack-up material. Design of experiment (DOE) using response surface methodology (RSM) by central composite design (CCD) is used to select twenty runs of experiment to evaluate the significance of tool geometry and parameters on thrust force during the drilling operation. The CCD is a very effective design for fitting a second-order response surface model. Figure 3.1 shows the approaches involved in investigating the properties of materials, conducting the drilling operation and analysis of hole quality characteristics after drilling. Understanding of the properties of material is necessary to ensure the compatibility of workpiece and drill bits. In this research, thrust force signature is the main measurement method of output characteristics of a hole quality. The setting and method used in operating dynamometer to measure the thrust force during drilling operation of stacked-up material are also briefed. Meanwhile, roughness and hole diameter are selected as hole quality assessments for the purpose of supporting the accuracy of results from thrust force generation. Subsequently, analysis of variance (ANOVA) is opted as a tool to reflect the significance of parameter and tool geometry on thrust force of stacked up material. The detailed methodological framework of the study is presented in Figure 3.2.

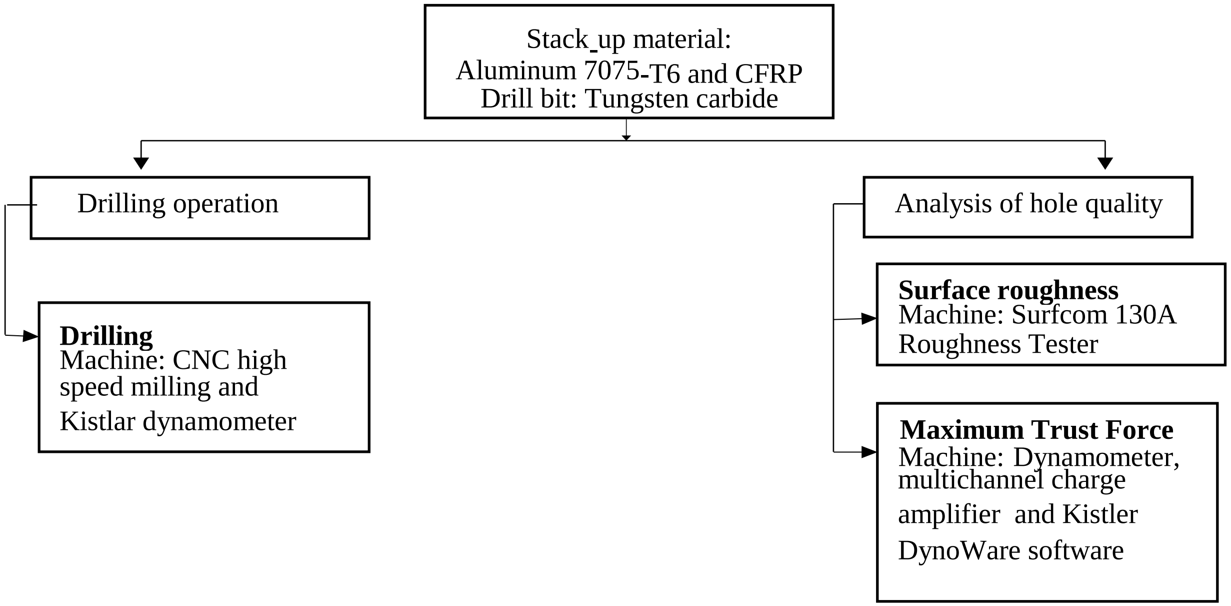

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Figure 3.1: Approaches and Test Conducted for the Research

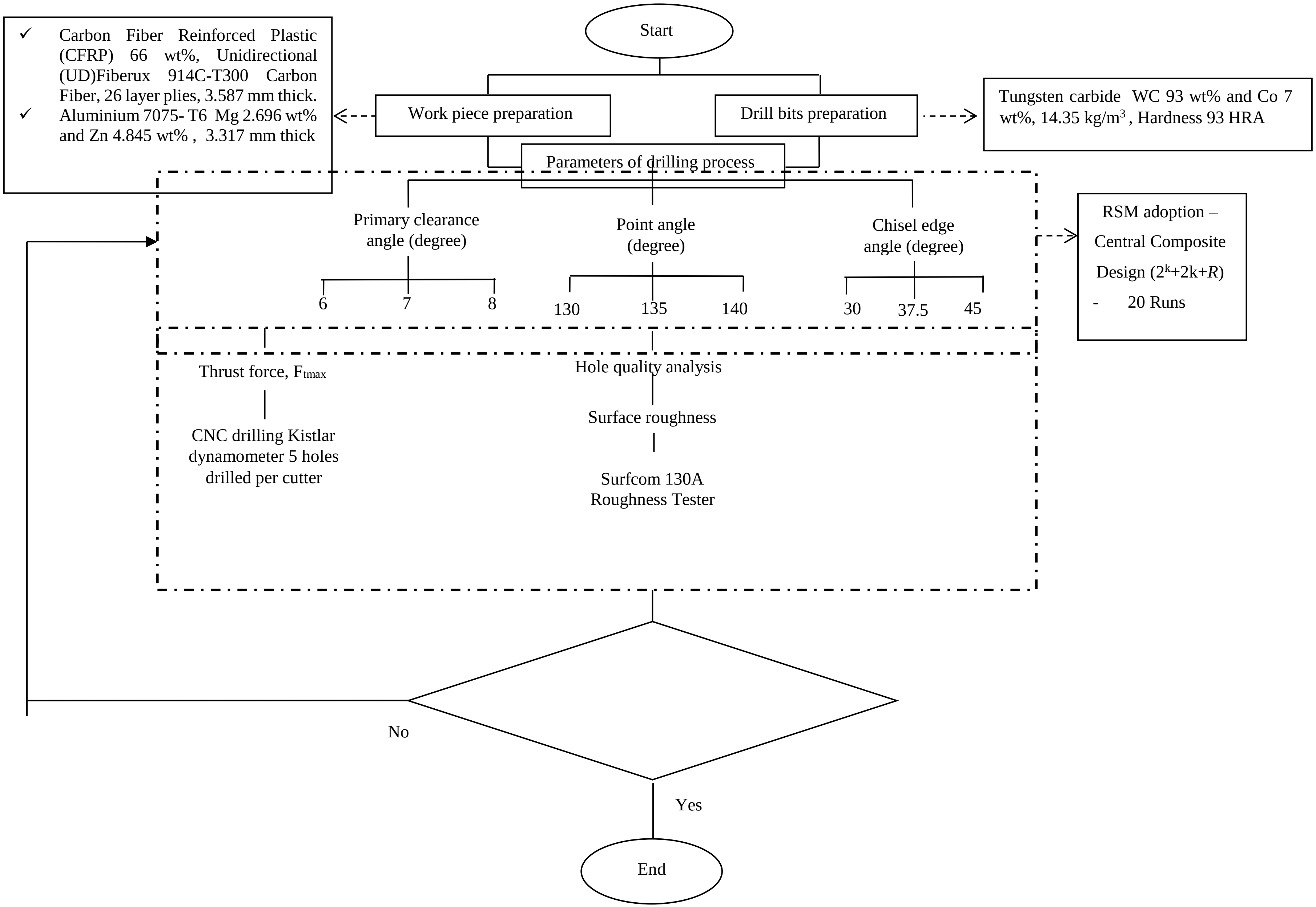


Fig. 3.2: Methodological framework of the study

3.2 Response Surface Methodology

Response Surface Methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables with the objective to optimize the particular response **[36].** The method also quantifies relationships among one or more measured responses and the vital input factors **[37].** The Design Expert v7.0 software was used to develop the experimental plan for RSM, as well as to analyze the data collected by the following steps **[37]:**

1. Defining the independent input variables and desired responses with the design constraints

2. Adopting the face centered central composite design (CCD) to plan the experimental design

3. Performing the regression analysis with the quadratic model of response surface, f

4. Calculating the statistical analysis of variance (ANOVA) for the independent input variables to establish the parameters that significantly affect the desired responses

5. Determining the situation of the quadratic model of response surface, f in order to decide whether the model requires the screening variables or otherwise

6. Obtaining the optimal design parameters with the design constraints

7. Conducting the confirmative experiment to verify the optimal setting of design parameters

Following the analysis of each response, multiple response optimizations were carried out, either by inspection of the interpretation plots, or with the graphical and numerical tools provided for this purpose. It was mentioned previously that the RSM models also able to quantify the relationships between one or more measured responses and the vital input factors. Through the design of experiments and the regression analysis, the modeling of the desired response with regards to the several independent input variables could be achieved. In RSM, the quantitative form of relationship between desired response and independent input variables could be represented as follows:

$$y = f(x_1, x_2, x_3, \ldots . x_n) \pm \varepsilon \quad (1)$$

where y is the desired response, f is the response function, $x_1, x_2, x_3, \ldots . x_n$ are the independent input variables, and Ɛ is the fitting error.

The identification of suitable approximation off will determine whether the application of RSM is successful or otherwise. The necessary data for developing the response models are generally collected by the design of experiments. In this study, the experimental data has adopted based on the face centered CCD and the approximation off was proposed using the fitted second order polynomial regression model, known as the quadratic model, written as follows:

$$f = a_0 + \sum_{i=1}^{n} a_i x_i + \sum_{i=1}^{n} a_{ii} x^2{}_i + \sum_{i<j}^{n} a_{ij} x_i x_j + \varepsilon \quad (2)$$

where a_i represents the linear effect of x_i, a_{ii} represents the quadratic effect of x_i, and a_{ij} reveals the linear-by-linear interaction between x_i and x_j. The use of the quadratic model off is not only to investigate the entire factor space, but also to locate the region of desired target where the response approaches its optimum or near optimal value.

3.2.1 Test for significance of the regression model

This test was performed as an ANOVA procedure by calculating the F ratio, which is the ratio between the regression mean square and the mean square error. The F ratio is also called the variance ratio, which is used to measure the significance of the model under investigation with respect to the variance of the terms included in the error term at the desired significance level, α.

3.2.2 Test for significance on individual model coefficients

The test forms the basis for model optimization by adding or deleting coefficients through backward elimination, forward addition, or stepwise elimination/addition/exchange. It involves the determination of the P value or probability value, which is usually related to the risk of falsely rejecting a given hypothesis. For example, a “Prob.>F ” value on an F test tells the proportion of time you would expect to get the stated F value if no factor effects are significant. The “Prob.>F” value determined can be compared with the desired probability or α level. In general, the lowest order polynomial would be chosen to adequately describe the system.

3.2.3 Test for lack-of-fit

As duplication of measurements is available, a test indicating the significance of the duplicate error in comparison to the model dependent error can be performed. This test splits the residual or error sum of squares into two portions; one is due to pure error which is based on the identical measurements and the other is attributed to the lack-of-fit based on the model performance. As previously, this F test statistic can be used to determine whether the lack-of-fit error is significant or otherwise at the desired significance level, α. The significant lack-of-fit indicates that there might be contributions in the regressor–response relationship that are not accounted for by the model. Additionally, the checks were required to verify various coefficient of determination, R2; these R2 coefficients provided the values between 0 and 1. In addition to the above, the adequacy of the model was also investigated by the examination of residuals **[36].** The residuals, which are the difference between the respective, observed the responses and the predicted responses using the normal probability plots of the residuals and the plots of the residuals versus the predicted response. If the model is adequate, the points on the normal probability plots of the residuals should indicate a linear trend.

3.3 Materials

3.3.1 Workpiece Materials

The stacked-up materials used in this study is CFRP and Aluminum 7075-T6. The density of CFRP and Aluminum is 1.601 g/cm^3 and 2.597 g/cm^3 respectively and the hardness value of the former is 61.8 HV while the latter is 68.4 HV. The composite specimen is of thickness 3.6 mm, whereby it is made up of 26 ply of unidirectional carbon composite and 2 ply of glass composite, joint together by carbon/epoxy prepregs. The thickness of carbon and glass composite are 0.125 mm and 0.08 mm each respectively. The layer stacking is symmetric, with the sequence of $[45/135/90_2$ $/0/90/0/90/0/135/45_2$ $/135]_{s.}$ Meanwhile, the metal panel used is Al7075 T6 with the percentage of alloying elements as follows: Al 92.459 wt%, Mg 2.696 wt% and Zn 4.845 wt%.

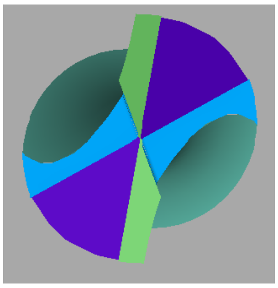
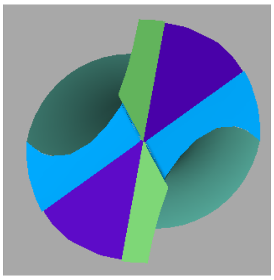
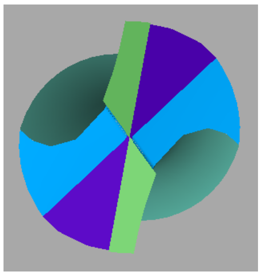
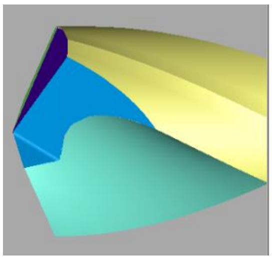
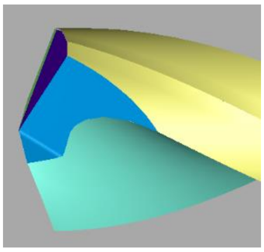
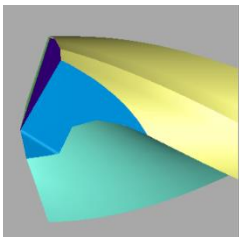
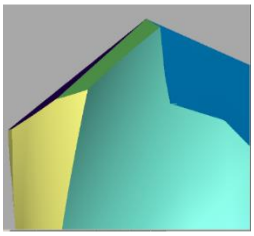
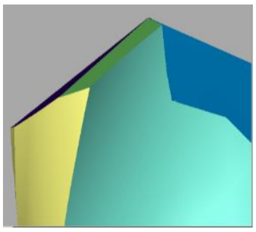
3.3.2 Cutting tools Materials

In this work, the twist drill bit is made of tungsten carbide (Figure 3.3) with composition of WC~ 93.36 wt% and Co~6.64 wt%. It has a density of 14.35 g/cm^3 and hardness value of 1625 HV, both of which are significantly higher than the workpiece material. The drilling tools can easily shear the surface of workpiece material without causing breakage.

Figure 3.3: Twist drill bit of one shot drilling

Three different parameters selected to be experimented are, primary clearance angle, point angle and chisel edge angle and two fixed parameters such as speed and feed rate are being studied in order to identify the optimum drilling parameters for stacked up CFRP/Al that comply to the specifications. The parameters set for each contributing factor are tabulated in table 3.2. Experiments are conducted based on central composite design, (CCD) using response surface method where 20 experiments with varying parameters are considered. Each experimental condition is repeated five times to reflect the quality of holes more accurately by taking the average readings besides monitoring the thrust force. For this experiment, 20 drill bits with bit diameter of 4.826 mm each are required.

Table 3.1 Set of Contributing Parameters.

Parameters			
Chisel Edge Angle	30 	37.5 	45 
Point Angle	130 	135 	140 
Primary clearance angle	6 	7 	8